SDMAY12-24 FINAL DOCUMENT

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Wind Turbine Simulation

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Section 1: Revised Project Plan

1.1: Abstract

As the United States pushes for green energy, many wind turbines have popped up all around the United States. With new forms of power, it is essential for students to be educated on the effects of wind and the modern day power system. The project described in this document takes wind measurements and simulates the power outputted to the system. With a system already in place to accomplish this, it was our job to improve upon the previous system.

1.2: Customer Needs

The smart grid simulation system must be capable of performing the following functions:

- Charge the battery bank using energy from the turbine when it is available.
- Power the grid using energy from the turbine when it is available.
- Power the grid using energy from the battery bank when the turbine is not providing power.
- The motor simulating wind speed needs to accurately reflect current wind speed conditions and the power generated should match the power curve of the turbine. See Figure 1.1.

Figure 1.1

1.3: System Plan

The original system fed the power from the generator straight to the battery. From there, the battery fed power to the inverter and then into the load. Since the inverter needs to have 21 volts to send power to the load, they had two 12 volt batteries in series. To improve upon the existing system, some rearrangement of circuitry and additions needed to happen.

First, studying the power system given was the key in obtaining a solution. By Running simulations in MATLAB and using LabVIEW to measure power flow, we were able to come up with some solutions. Instead of feeding power from the turbine straight to the battery, we decided it was best to send power straight to the inverter. The problem is in the interior turbine circuitry. This circuitry needs to see 7 volts to operate. Because of this minimum operating

voltage of the turbine circuitry, the batteries need to be in parallel to the turbine, where the batteries supply the minimum operating voltage.

Upon researching different ways to increase the voltage, we came across many different circuits. We didn't want to use the circuitry already in place in the turbine, so we decided to disassemble it and make our own circuitry. After narrowing the options down, we decided to use a buck-boost converter (see section 11). This circuit takes an input DC voltage and magnifies it to a level designed, which in our case is between 21 and 34 volts (see Inverter section 13.2).

The turbine generator outputs a variable frequency sinusoidal 3-phase wave. We want a single-phase DC signal to be sent to the buck-boost converter for best results, so more circuitry would need to be pieced into the schematic. The best way to go from a 3-phase signal to a 1-phase signal, while converting to DC power, is to use a rectifier (see section 10). From the use of a rectifier and a buck-boost converter, our inverter gets the 21 volt input it needs in order to power the load.

The next part of the system that needs revising is the use of the battery. Since the battery is used as a secondary source of power, it should only be in use when the wind is too low to power the system. Also, because we don't want to destroy expensive batteries, they need to be charged when the voltage gets too low and also not exceed the 26 max voltage. This can be done using a switch and LabVIEW to determine when the turbine needs to switch from powering the load, to charging the battery or both.

Lastly, since inexperienced users could be operating the system, a simple, easy to use, LabVIEW interface will be in place. This interface will assist in running the system, as well as monitoring different voltage and current levels in the system. To make sure users are running the system correctly there will be an operation manual to follow step by step start up and shut down instructions (see Appendix A).

1.4: Functional/Non-functional Requirements

Functional:

- The turbine circuitry (sections 10-12) will generate a 24V DC output.
- The turbine generator will generate a 400W peak output.
- The motor will simulate outdoor wind speed.
- The anemometer and wind vane will transmit wind profiles from locations on campus.
- The turbine output current will be accurate for the input wind speed.
- The turbine will supply the battery bank when the batteries are below 24V.

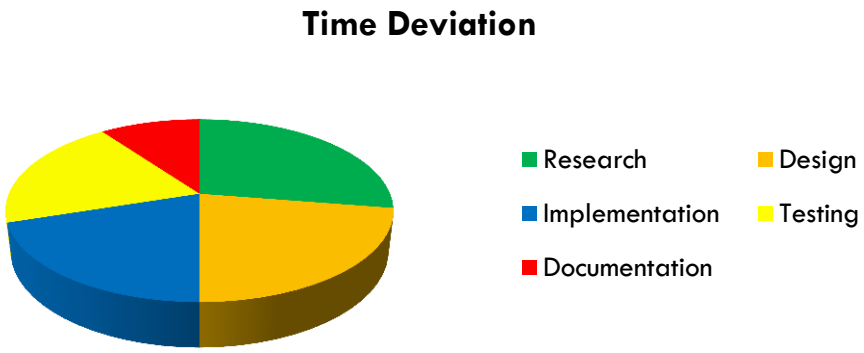
Non-Functional:

- The project will be documented through technical manuals and in-depth schematics.
- The new motor will be remounted and be on a stable operating platform.

1.5: Budget

Motor	$175
Mounting/Coupling	$70
Circuitry	$55
Hardware	$50
Total	$350
Budget	$500

1.6: Schedule



Section 2: Revised Project Design

2.1: Original System

As stated in section one of this document, the original system had the load powered by batteries. The simulated wind energy was used to charge the batteries. Figure 2.1 and 2.2 shows the project handed down to our group from the previous year.

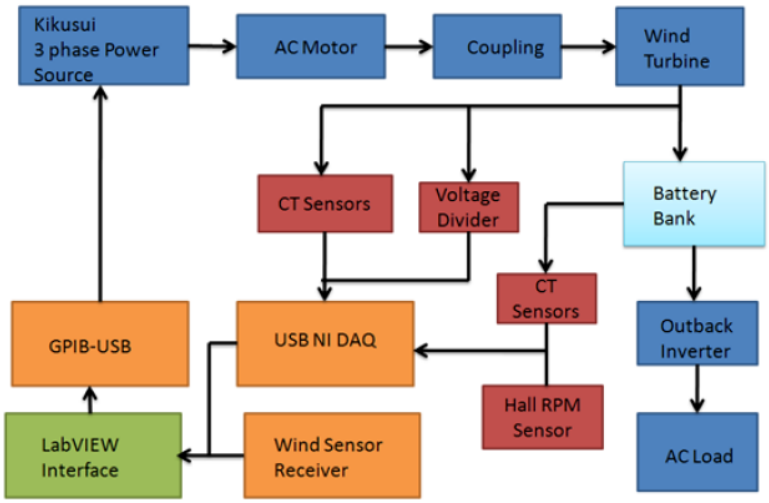


Figure 2.1

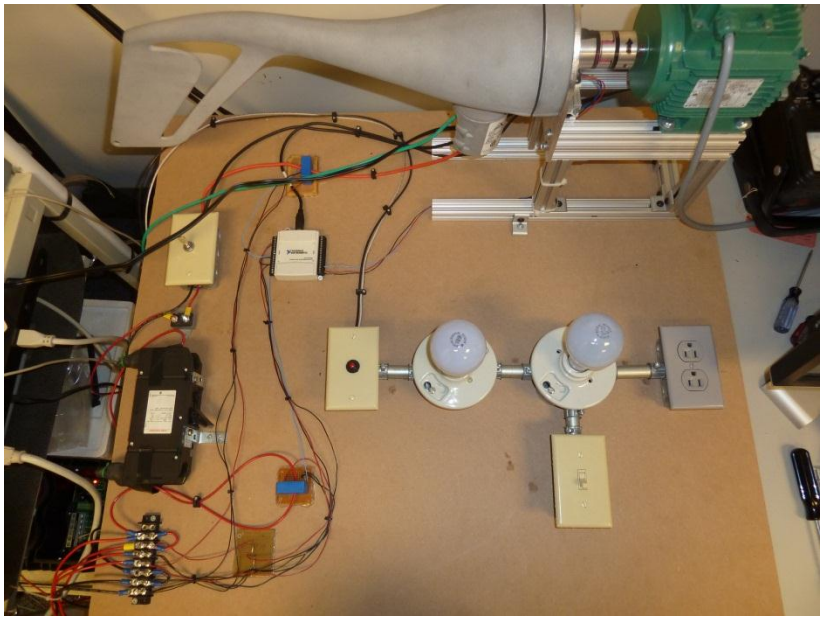


Figure 2.2 – Existing system from previous year

2.2: Intended Use

The main purpose of this project is for future students to observe a small wind turbine system. Since all experiments can be done in the lab area, this creates a great learning environment. Through user interface using LabVIEW, a single user can monitor and, if all goes as planned, control the turbine system. Even though a single person could maintain by his or herself, the lab requires at least two individuals at all times in the lab.

2.3: Operating Environment

All simulations are controlled in a lab environment where the wind turbine is mounted to a table. Because of safety reasons the wind turbine is not allowed to be placed on a building in the university. Therefore, the project is centrally located in a lab environment. Since the turbine is controlled by an AC motor via coupling, LabVIEW picks up readings from a wind sensor that is placed outside. The reason for the wind sensor is to accurately simulate real wind conditions.

2.4: System Updates

The finalized system successfully achieves all of the goals described in the Revised Project Plan section. Through rearrangement of circuitry, the power from the turbine now flows directly to the inverter. Batteries are bypassed unless the system needs the backup energy or when the batteries need charged. The buck-boost converter (section 11), PWM (section 12), diode rectifier (section 10), and new motor/mount (section 7/8) were all added to the final system so the motor is the primary power source for the load. Figure 2.3 and Appendix B shows the schematics and an overview of the new system.

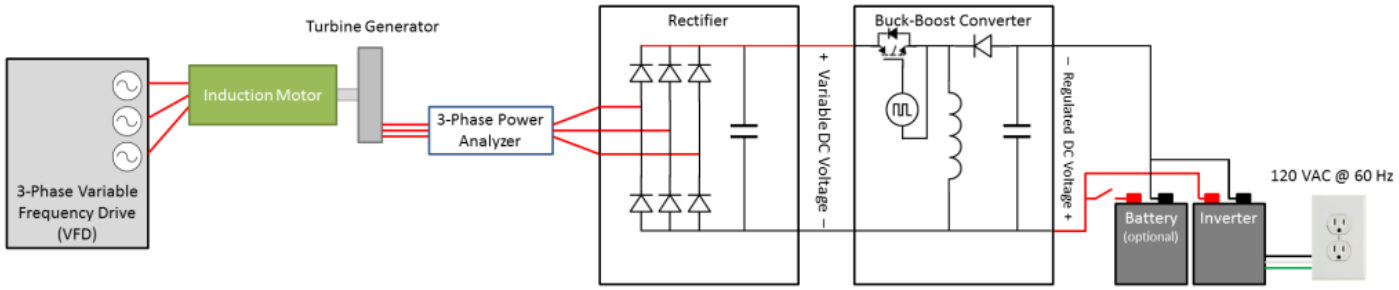


Figure 2.3 – Simplistic Model of Improved System

Section 3: Implementation and Testing

3.1: Plexiglas Boxes

All new circuitry (sections 10 – 12) and current transducers (CT) are incased inside clear Plexiglas boxes. This allows protection of the circuitry and safety for the user. All input and output ports are mounted with banana jacks on the casing of the boxes. This is intended for easy wiring of the system. Also, this allows the user to make measurements at every input/output.

3.2: Full System Testing and Implementation

Figure 3.1 shows a schematic of the system. Before implementation of any hardware, all testing was done through a MATLAB simulation. First, we would calculate the desired value of a passive device. Then we would use that value in the MATLAB simulation and run a transient analysis. After verification, we would then order the part with the correct specifications. Upon arrival of the part, we would build a circuit prototype on a breadboard. Next, we would use multimeters, oscilloscopes, LabVIEW data, or a combination of all three to verify earlier results seen through MATLAB. Then, the circuits would get soldered together and mounted in their designated Plexiglas box. Finally, a full system test would be conducted verifying all circuitry behaving as planned. If at any point, there was a device or circuit that did not meet expected results, then we would go back to step one of calculations and repeat.

There were several times when testing the full system that devices would fail or become damaged. When this occurred, then demounting and repair was needed with circuits that were considered to be in their final state (i.e. mounted inside Plexiglas box). Most of the time spent in this project was in testing and implementation. This can be seen in the pie chart in section 1.6.

Notice in Figure 3.1 how voltage and current measurements are taken from the circuit and fed back into the gate of the IGBT. These green lines in Figure 3.1 are modeling the feedback system that is implemented into LabVIEW. See section 5 for full development of the feedback system that controls the signal going into the gate of the IGBT. This signal from LabVIEW passes through a PWM circuit (section 12) then goes to the IGBT that is implemented in the Buck-boost circuit (see section 11).

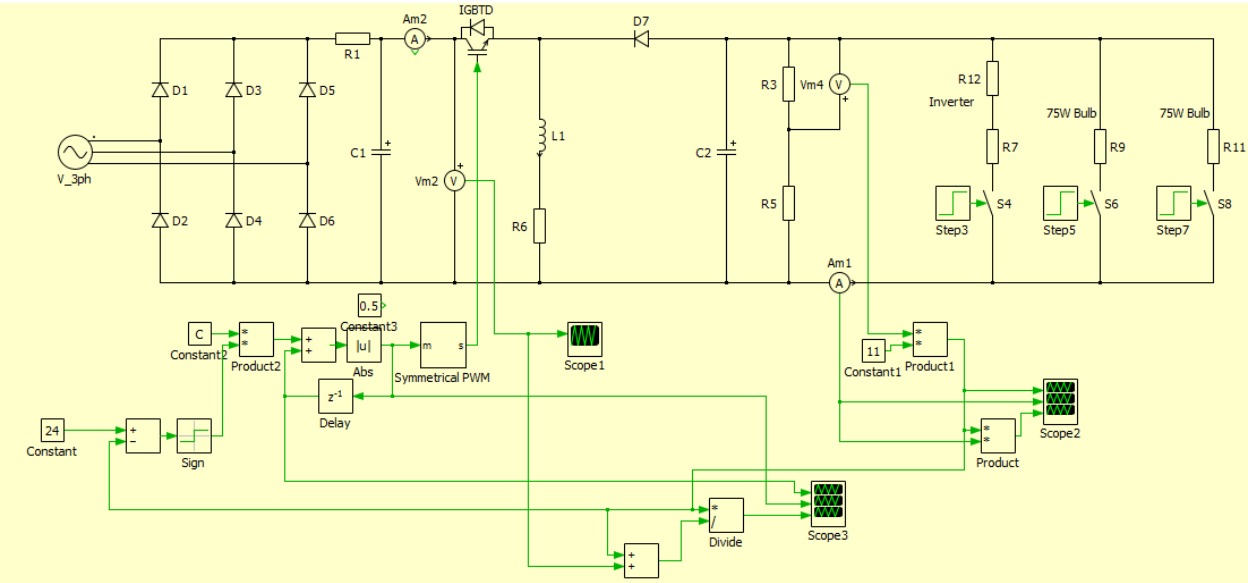


Figure 3.1: MATLAB PLECS Modeling

3.3: Diode Rectifier Testing

With the box setup, the user just needs to plug in the three phases from the generator into the box plugs. When testing the rectifier out, the most important aspect is a clean DC output signal. In Figure 3.2, the user can observe that the output is as desired.

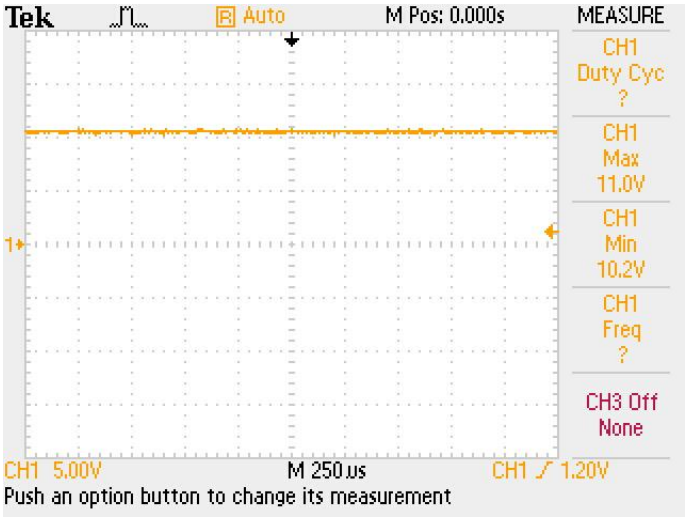


Figure 3.2

3.4: Buck-Boost Converter Testing

The buck-boost requires two wires designating the output, the input and output voltage measurements, and the PWM input to the circuit. In order for this circuit to work correctly, a DC output between 21 and 34 volts is required. From the testing, it has been determined that it does indeed work accordingly.

3.5: PWM Testing

Looking at the labels on the box, the user needs to make sure the plus and minus 15 V (V_{dd} and V_{ss}), the input from the DAQ, and the output cables are plugged in appropriately. With different duty cycles, the width of the wave gets smaller or larger. As you can see below in Figure 3.3, the wave's output is behaving accordingly.

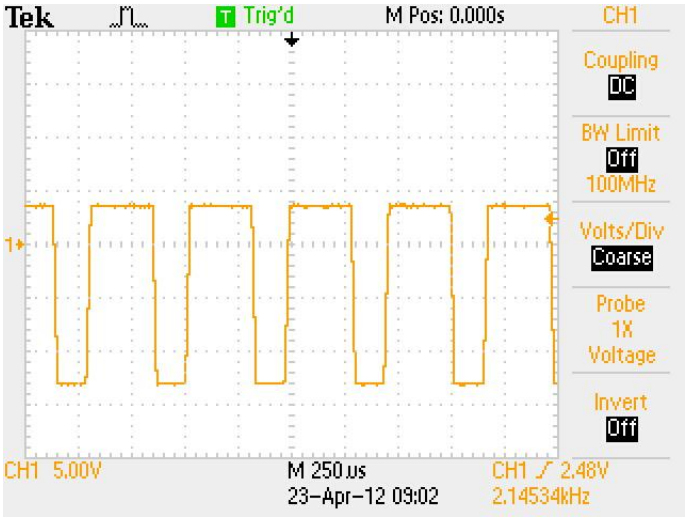


Figure 3.3

3.5: New Motor/Mount

When we got the new motor, we needed to make sure our power output from the generator was matching the power curve in Figure 1.1. LabVIEW is used to control the voltage levels to the motor for simulations and we adjusted the voltage inputs to model the correct output power. Also, with a new motor comes a new mount (see sections 7 and 8). The new mount keeps the motor and turbine stable with little oscillations to prevent energy losses.

Section 4: Full System Overview

Refer to Figure 2.3 for the system overview. First, the computer co1301-sdmay12-24 takes in real wind data through LabVIEW via an anemometer. Then, LabVIEW controls the Ironhorse induction motor using the Kikosui 3-phase variable frequency drive or VFD (for more on LabVIEW controls and measurements see section 5). The control of the motor follows the curve in Figure 1.1. Also, the control of the motor depends on max RPM ratings and any changes in the load. The control of the motor will use V/Hz techniques and/or slip techniques (for more information on motor control see section 7).

Next, the VFD powers the motor to turn the rotor. Through the coupling, the rotor of the motor turns the shaft of the wind turbine generator. The turbine generator then produces a 3-phase variable voltage and frequency (see section 9). Now, the variable AC voltage goes through a diode rectifier to produce a variable DC voltage (see section 10). This DC voltage can now be regulated.

Figure 2.3 shows the regulated DC voltage, batteries, and inverter all connected at the same node (red wire). By understand Kirchhoff's Current Law (KCL), the regulated DC voltage, the batteries voltage level, and the inverter input voltage will be equal. The motor will spin faster or slower depending on the speed of the simulated wind. This speed of the motor or, another way to say it, the RPM's of the rotor determine the DC voltage coming out of the diode rectifier. This DC voltage can either be too low for the batteries/inverter nodes or too high (To understand maximum and minimum levels of the batteries/inverter node see section 13). Therefore, we implemented a buck-boost converter that can either boost the voltage up or "buck" the voltage down (see section 11). The controls to the buck-boost come from a PWM wave (section 12) that is manipulated from LabVIEW commands.

Lastly, when the desired voltage levels are met from the buck-boost, the inverter will turn on. This means that the Status Inverter light is green. When this light is green, then at this point the user can turn on a light bulb if there is not one on already.

Section 5: LabVIEW Interface

5.1: Overview

Most of the components in our system interact with the host computer through National Instruments LabVIEW software. This software allows a user to create a "Virtual Instrument" (VI), which may access various inputs and outputs of the computer. These VIs have a front panel user interface to allow a user to control the system, or observe measurements from the system. The functionality of the VI is defined in a block diagram, which connects various functions and "subVIs" using virtual wires to define the data flow.

5.2: Available Inputs and Outputs

Arduino USB Serial Device

Wireless Wind Speed Data (Input to LabVIEW)

Kikusui PCR6000W2 Three Phase Power Supply

AC Voltage level (Output from LabVIEW)
AC Frequency (Output from LabVIEW)
Current (Input to LabVIEW)
Real Power (Input to LabVIEW)
Complex Power (Input to LabVIEW)
Power Factor (Input to LabVIEW)

Magtrol 6530 Power Analyzer

Voltage level for each phase (Input to LabVIEW)
Current level for each phase (Input to LabVIEW)
Power calculations for each phase (Input to LabVIEW)
Power Factor calculations for each phase (Input to LabVIEW)
Frequency measurement (Input to LabVIEW)

National Instruments USB-6008 Low-Cost Multifunction DAQ

PWM Frequency (Output from LabVIEW)
PWM Duty Cycle (Output from LabVIEW)
Battery Switch (Output from LabVIEW)
Current measurements from CTs (Input to LabVIEW)
Voltage measurements from voltage attenuators (Input to LabVIEW)
Hall Sensor signal for RPM calculation (Input to LabVIEW)

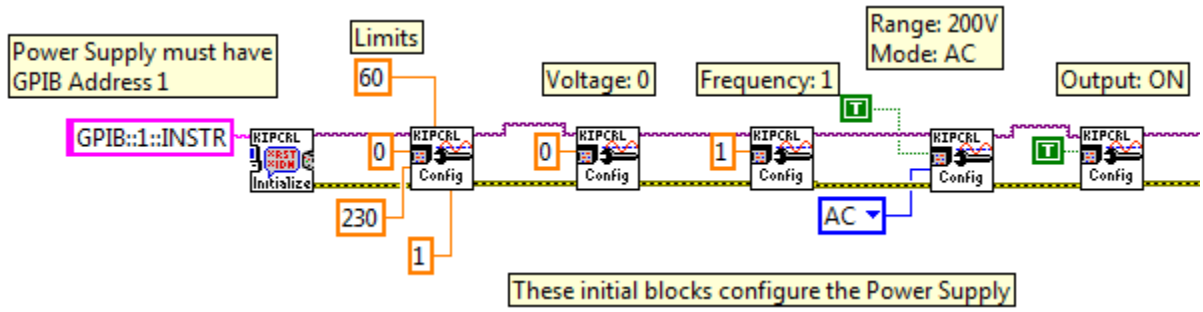
5.3: Design Details

The purpose of the LabVIEW software is to control the motor that is used to simulate wind, control the PWM generator used by the Buck-Boost converter, and display measurements to the user. The motor is controlled by setting the AC Voltage level and AC Frequency on the Kikusui PCR6000W2. The current implementation uses a feedback control loop for this process, where the actual RPM is compared to the "synchronous" RPM. See the Motor section of this document for more details regarding motor control. The frequency and duty cycle of the PWM generator are controlled using analog voltage outputs of the USB-6008. These DC outputs have a range of 0-5V, with 12-bit resolution, and about 1 ms update latency. The signals are ground referenced. All of the ports labeled "GND" are connected to the same ground reference. This reference should be the same as the common 0V input to the PWM generator.

5.4: Implementation Details

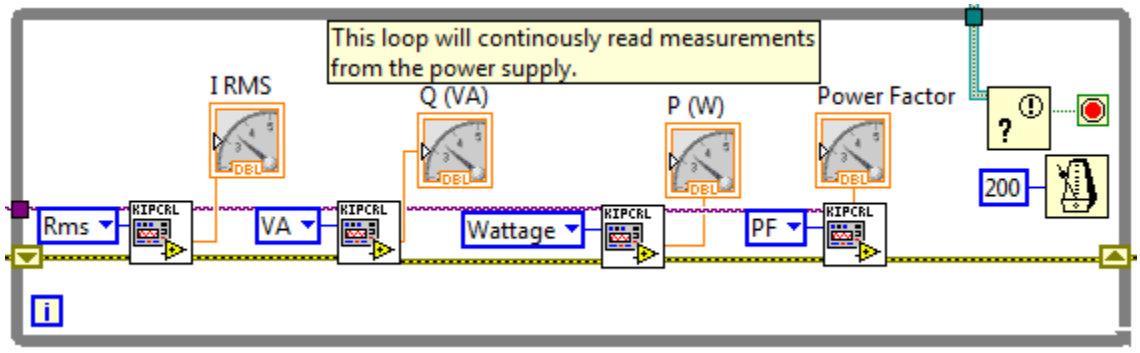
All of the communication with the Kikusui PCR6000W2 and the Magtrol 6530 is done through a GPIB connection. Both of these devices have LabVIEW drivers available from the manufacturer, so the complicated details of the GPIB syntax is handled behind the scenes.

- KIPCRL Config VI used to configure PCR6000W2 settings



The above block diagram shows a sequence of KIPCRL subVIs that configures the PCR6000W2 with predefined constants when they are executed. Notice that the wires connect one block to the next. A block will not execute until all of the inputs are ready. This diagram executes in order from left to right.

- KIPCRL Monitor VI used to monitor output conditions



This diagram shows several measurements that are taken continuously, and then displayed on "Indicators" on the front panel.

- Magtrol 6530 Config VI

- Magtrol 6530 Read VI

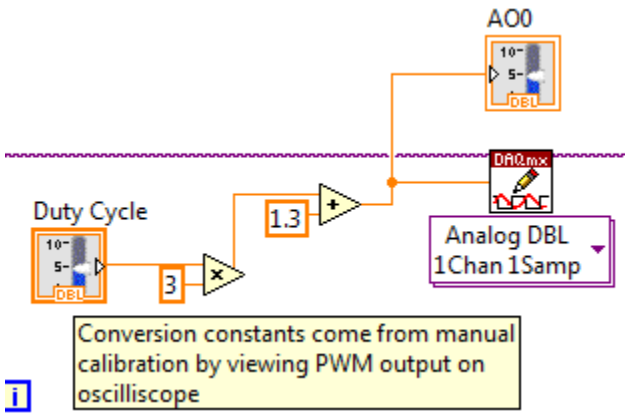
All of the inputs and outputs on the USB-6008 are accessed through the DAQmx driver framework. This is one of the National Instruments drivers. It may be difficult to understand for new LabVIEW users.

- DAQmx Start Task VI

- DAQmx Write VI

- DAQmx Read VI

- DAQmx Stop VI



The above block diagram shows a user-input control value being converted from Duty Cycle to a Voltage Output value. The voltage value is displayed on the indicator AO0, and written to the USB-6008 with DAQmx.

More complicated graphical programming techniques are used to perform execution control of the VIs themselves, combine measurements together, calculate RPM, etc. Check on ni.com/isu for help with learning to use LabVIEW, or e-mail brian.alexander@ni.com with any questions about the code used in this project.

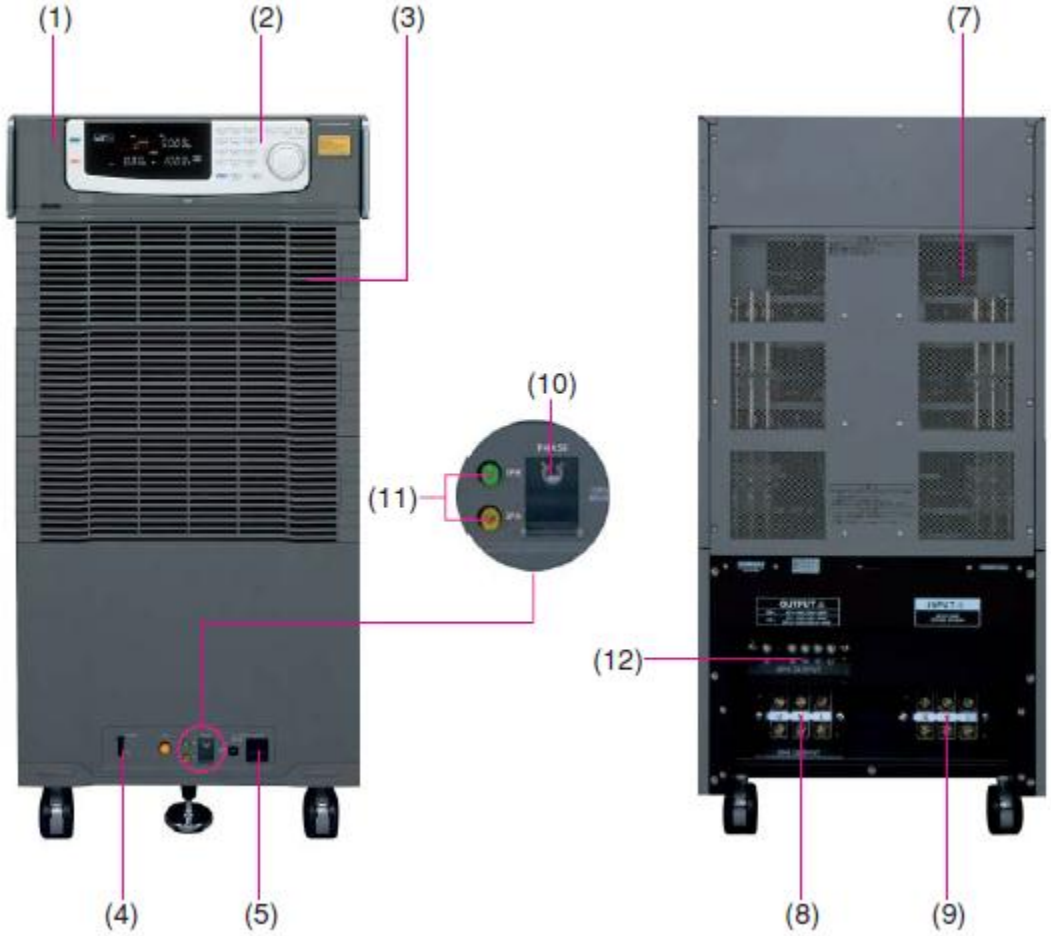
Section 6: Three Phase Power Source

In this project, wind power is simulated using an electrical motor that is powered and controlled using a variable voltage, variable frequency, three phase power supply. The model of this power supply is a Kikusui PCR-6000W2. It can be operated manually using the front control panel, or through a GPIB connection. It will measure the output current, and power factor, and calculate the Apparent (VA), Reactive (VAR), and Real (W) power levels. This power source is adequate for controlling the induction motor, as a variable-frequency Drive (VFD). Kikusui currently provides software drivers for LabVIEW, Visual Basic, and LabWindows/CVI. The drivers allow the user to set the power supply voltage or frequency, and read the measured power quantities into the host computer. These software drivers cover the details of the underlying GPIB communication syntax.

Input Voltage (From Coover Electrical System)	230 V, Single Phase
Input Current (From Coover Electrical System)	48 A or less

The output of the power supply must be set to 3-phase, and the range should be set to 200V. Setting the range to 200V (input) allows a user setting of up to 300V (output). See the product manual for more information.

PCR-6000W2
(Single-phase/three-phase changeover type)



(1)	I/O slot to install an optional expansion card.
(2)	The large color fluorescent character display tubes (VFD) allow a bright and clear display. Operation is possible by using function keys, or ten keys and jog/shuttle combination. The angle of the panel surface can be changed in 2 steps.
(3)	Air intake port for forced air cooling, equipped with a built-in air filter.
(4)	Power switch
(5)	Output receptacles (125 VAC, 10 A max.)
(6)	Input voltage range selector switch. (Only for PCR2000W and PCR4000W)

(7)	Forced air cooling system exhaust port
(8)	Single-phase output terminal board
(9)	Input terminal board, applicable to 85 to 132 V / 170 to 250 V. (PCR8000W, 12000W, 6000W2, and 12000W2 however, use only the 170 V to 250 V range.)
(10)	Single-phase/three-phase selector (this switch is equipped with a misoperation prevention cover)
(11)	Single-phase/three-phase indicator
(12)	Three-phase output terminal board

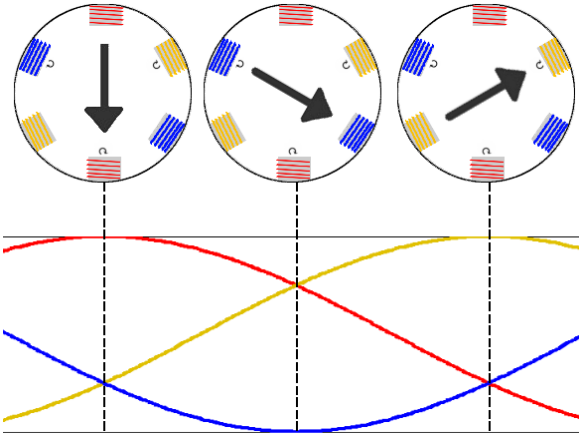
Section 7: Motor

The electric motor used in this project is a 3-phase AC induction motor. Specifically, it is an Ironhorse MTCP-1P5-3BD36 motor purchased from Automation Direct in February 2012.

Horsepower	1.5 HP
Max Frequency	60 Hz
Max Voltage	230 V
Full Load Amps	4.08 A
Full Load RPM	3570 RPM
Minimum RPM (Constant Torque)	900 RPM
Minimum RPM (Variable Torque)	360 RPM
Full Load Torque	2.2 Ft-lbs
Locked Rotor Torque	6.4 Ft-lbs
Break-down Torque	7.9 Ft-lbs
Pole Pairs Per Phase	1
Wiring	Double Star (YY)

See www.automationdirect.com for more specifications.

An induction motor works by creating a rotating magnetic field, using windings of wires called poles. Each pole is connected to one of the three phase inputs. The diagram below illustrates how the 120° separation of the power phases causes the generated magnetic field to rotate uniformly.



Picture Credit: Wikipedia.org

This part of the motor which does not move is called the "stator". The input frequency to the motor can be used to change the speed at which the magnetic field rotates. This speed is called the synchronous speed. Since our motor has one pole pair per phase, the synchronous speed is 60 times the input frequency. That is, a 60 Hz power input will produce a 3600 RPM synchronous speed.

The part of the motor that spins is called the "rotor". In an induction motor, the rotor spins slightly slower than the stator. It is called an "asynchronous" machine. The "slip" of the motor is a calculation that represents how much slower the rotor is spinning.

$$slip = \frac{synchronous\ speed - rotor\ speed}{synchronous\ speed}$$

As the motor is loaded down with torque, the rotor speed will decrease, causing the slip to increase. This effect can be counter-acted by increasing the voltage to keep the slip around 1-5%. If the load torque decreases, the voltage should be decreased as well in order to prevent the windings from being overcharged. A simple method to control the motor speed involves measuring the rotor speed, and adjusting the input voltage so that it is slightly less than the synchronous speed.

Simple motor control example:

Desired Rotor Speed: 1000 RPM
Desired Slip: 0.03 (3%)
Synchronous Speed = 1000 / (1 – 0.03) = 1030.9 RPM
Power Supply Frequency = 1030.9 / 60 = 17.18 Hz
Adjust supply voltage so the measured rotor speed is close to 1000 RPM.
When the load torque changes, the voltage should be changed to maintain 1000 RPM rotor speed.

Section 8: Motor and Generator Mounting

8.1: New Motor/Mount

Due to the low power output of the previous motor, our group found it was necessary to obtain a new motor that could handle the load. See section 7 for more details on the Ironhorse, 1.5 hp, induction motor. The dimensions of the new motor are different from the last motor. Therefore, we acquired new strategies in mounting. Figure 8.1 shows a depiction of the new motor and the mount. This CAD drawing was done using Sketchup 8.

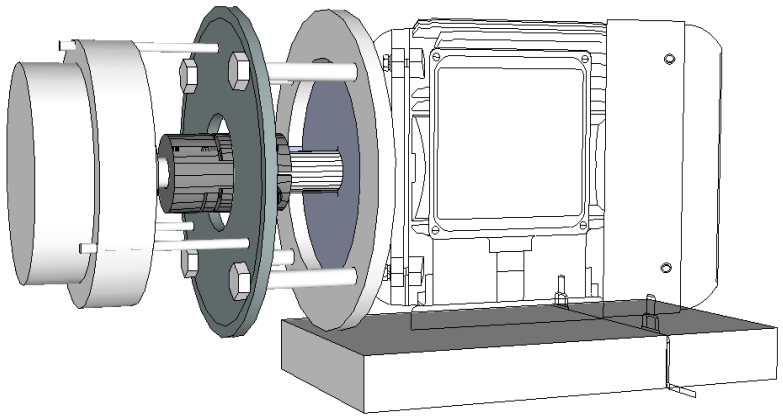


Figure 8.1: New motor/mount

8.2: Strategy

Figure 8.3 shows the old motor and mounting scheme. Notice how the body of the turbine is still intact in this old set-up. The turbine body plus the interior circuitry allows the center of gravity to move more in the turbine's direction, causing necessary structure under the turbine/generator. This year's team (SDMay12-24) has dismantled the body of the turbine and removed the interior circuitry. We are then re-building the circuitry, so we have full control of the system (see sections 9 – 12). By losing this extra weight and by adding a new motor, that is approximately 60 lbs, we can reduce the amount of mounting materials needed. We decided on a strategy that involves suspending the generator from the motor through a mount. This can be observed in Figure 8.1.

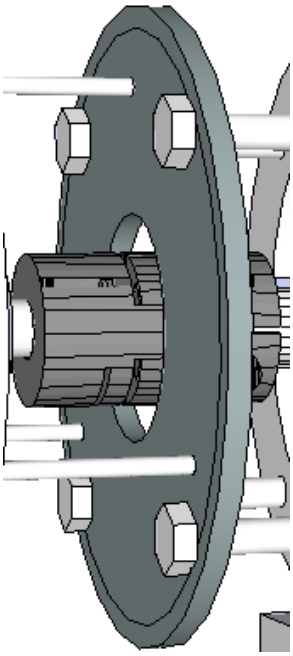


Figure 8.2: Mount (Grey) and Coupling (Black)

First, let us focus on the coupling device used to attach the rotor of the motor with the shaft of the generator. The black device in Figure 8.1 and 8.2 is the coupling. We only needed to order half of the coupling that attaches to the rotor. This was custom built to fit on the rotor of the Ironhorse induction motor. Next we needed to make a quarter inch plate of metal that could attach the motor and generator. Also, the plate needed a hole in the middle where the rotor-coupling-shaft could fit through. The grey plate in Figure 8.1 and 8.2 shows this mounting scheme. The plate was made out of stainless steel and was cut to the desired dimensions. The final motor/mount can be seen in Figure 8.4.

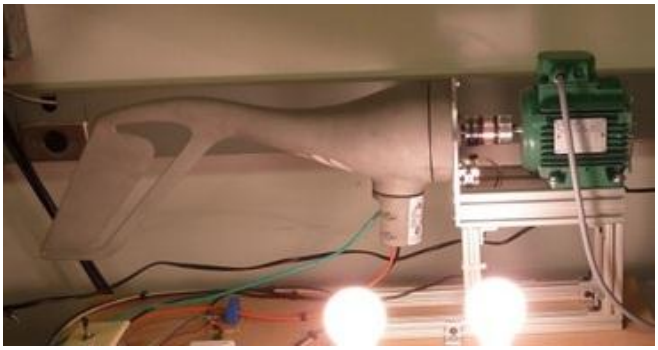


Figure 8.3: Old motor and mount

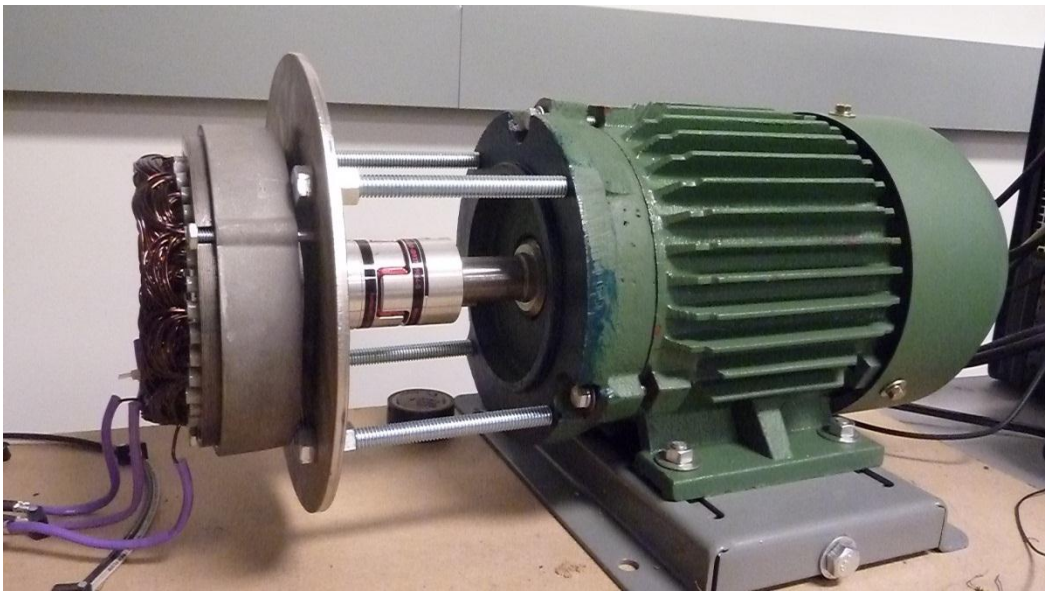


Figure 8.4: The new motor and mount with the body of the turbine taken off.

Section 9: Permanent Magnet Generator

As we took apart the housing for the turbine we found that the generator used in this specific model of turbine is operated with a permanent magnet. This is very common for small scale wind turbines. While knowing the exact physics and equations behind this device's operation may not be critical to the operation of our small scale wind turbine system, it is good to have some knowledge of its operation.

In this type of generator, the excitation field is provided through the permanent magnet rather than through a coil. Rotation of this permanent magnet, which is normally done through wind power but in our case through the motor, generates electric current in the coils surrounding the magnet. Our generator outputs a three-phase signal therefore the three phases are designed to be located 120 degrees apart in order to create the appropriate phase angles.

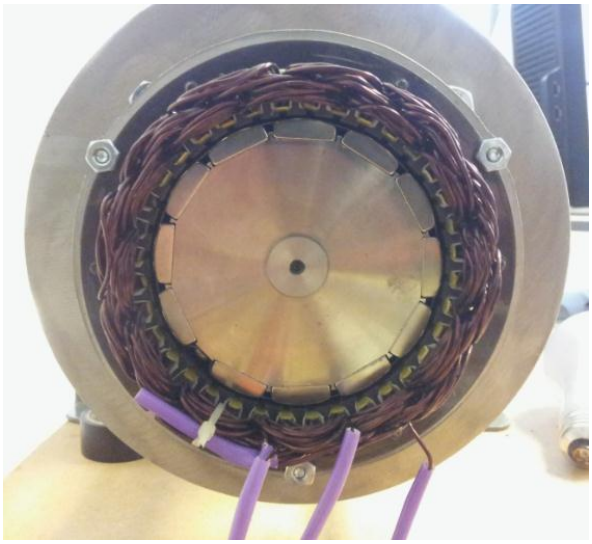


Figure 9.1

Section 10: Three-Phase Diode Rectifier

10.1: Overview

The three phase output signal coming from the turbine generator is a variable voltage and variable frequency. In order to produce a useable signal, some conversion is required. The diode rectifier is the first step in this conversion process. This circuit takes the 3 voltage outputs from the generator and converts to one nearly DC output. The output is nearly DC because there is going to be a reasonable amount of noise or ripple on the signal. This noise is easily accounted for by adding a simple low-pass RC (resistor-capacitor) filter.

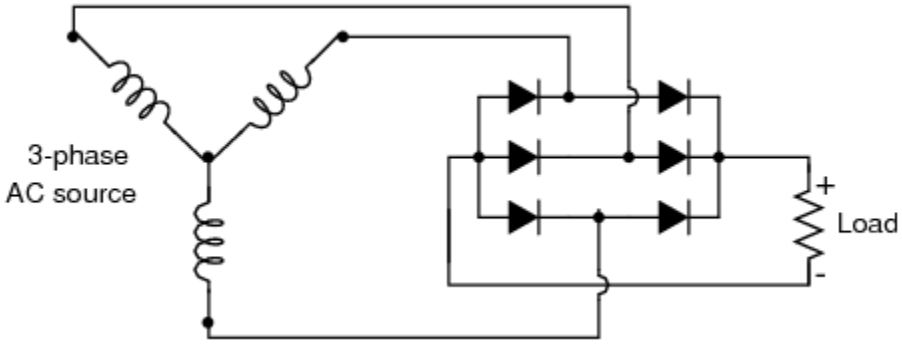


Figure 10.1

The figure above is the schematic for the three-phase full-wave bridge rectifier. As stated before, the wind turbine generator provides a three-phase output which can be modeled as a three phase AC voltage source star (wye) connected. In our application, we are dealing with large amounts of current flowing through these diodes therefore we made sure to purchase diodes strong enough to handle these currents.

10.2: Calculations

There really is only one calculation needed when analyzing this circuit and that is the output voltage. For an ideal three-phase full-wave rectifier, the average output voltage is

$$V_{\mathrm{dc}} = V_{\mathrm{av}} = \frac{3\sqrt{3}V_{\mathrm{peak}}}{\pi}\cos\alpha$$

Where:

$V_{dc} = V_{av}$ = The DC or average output voltage
V_{peak} = The peak value of the sine wave
V_{rms} = The root-mean
α = firing angle of the thyristor (In our case this is 0 because all diodes are used for rectification)

One additional calculation that is needed to be made is to find the cut-off frequency of the low pass RC filter used to smooth the output of the diode rectifier

$$\omega_c = \frac{1}{RC} \qquad f_c = \frac{1}{2\pi RC}$$

Where:

ω_c = The cut-off frequency in radians
f_c = The cut-off frequency in hertz
R = Value of the resistor
C = Value of the shunt capacitor

Section 11: Buck-Boost Converter

11.1 Introduction to the Buck-Boost

The buck-boost converter is the driving force of the circuitry. After the voltage has been properly rectified from the diode rectifier (Section 10), then the buck-boost can start using the DC input voltage from equation (10.1). The buck-boost is designed to either "buck" the voltage down or "boost" the voltage up. This is ideal due to the varying voltages from the varying wind speeds. The output voltage must maintain a range that is suitable to the load (see Inverter section 13).

Figure 11.1 shows the components of the buck-boost. Observe that the input voltage is the DC voltage from equation (10.1) and the load, R, is the inverter (see section 13). The switch, S, is an IGBT (transistor), which is controlled through the PWM circuitry (see section 12).

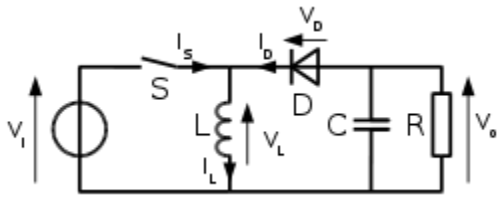


Figure 11.1: Buck-Boost Converter

$$V_o = -\left(\frac{d}{1-d}\right)V_i \qquad (11.1)$$

Equation (11.1) shows the gain of the circuit, where d is the duty cycle (see section 11.2). Notice the negative sign, which shows the output voltage is inverted with respect to the input voltage. By simply connecting the wires to the buck-boost in the appropriate manner, one can disregard the negative sign.

11.2 Technical Aspects

The main driving force of the buck-boost originates from the switching frequency, fsw, and the duty cycle, d. As seen from equation (11.2), the switching frequency can be defined as how many times the switch, S, turns on and off per second. Of course there is a limit to how fast the switch can turn off and on. Most transistor data sheets have a switching frequency max. The IGBT used in this project operates at a maximum switching frequency of 3 kHz. As seen from equation (11.3), the duty cycle is a percentage of the amount of time the switch is on.

$$f_{sw} = \frac{1}{t_{ON} + t_{OFF}} \qquad (11.2)$$

$$d = \frac{t_{ON}}{t_{ON} + t_{OFF}} \qquad (11.3)$$

Where:

t_{ON} = The amount of time the switch is ON.

t_{OFF} = The amount of time the switch is OFF.

Therefore, by controlling the duty cycle to its appropriate value, we can use equation (11.1) to properly control the output voltage of the buck-boost. Furthermore, the inductor resistance directly impacts the gain of the circuit in the boost mode of operation. Also, the size of the inductor is limited by equation (11.4). In other words, the inductance must be large enough to support the load and circuit parameter, but not too large. If the inductor is too large (i.e. large resistance) then the gain will diminish as the duty cycle increases. This can be seen from equation (11.5).

$$L > \frac{(1-d)^2 R_{load}}{2 f_{sw}} \qquad (11.4)$$

$$V_o = \frac{V_i}{1-d+r_L(1-d)} \qquad (11.5)$$

Where:

r_L = the ratio of the inductor resistance to the load resistance.

11.3 Controls

The duty cycle and the switching frequency are controlled through the PWM circuit (see section 12). In Appendix B-1 the circuit uses a voltage divider to measure the output voltage, which is sent to LabVIEW through the NI-DAQ-6008. Based on measurements, LabVIEW decides on how to change the duty cycle through feedback loops. When operating the buck-boost with no load (i.e. the inverter is off) the PWM duty cycle can be reduced. In doing so, the output voltage will not increase exponentially.

It is only by electrically isolating the signals between the circuitry and the NI-DAQ-6008 that measurements can be achieved. The reasoning lies with how the NI-DAQ-6008 has to be grounded and how the buck-boost common ground inverts. This can be achieved using an optocoupler (see Appendix B-7).

Section 12: Pulse Width Modulation

12.1: Overview

The operation of the buck/boost converter hinges on a pulse width modulated (PWM) signal. As explained earlier in section 11, the characteristics of this signal is what determines the output voltage from the converter. There are many ways to produce a PWM signal. We choose to use our knowledge learned in EE 230 and EE 330 by feeding the output of an inverting integrator into a non-inverting comparator with hysteresis to create this square wave signal as shown in Figure 12.1.

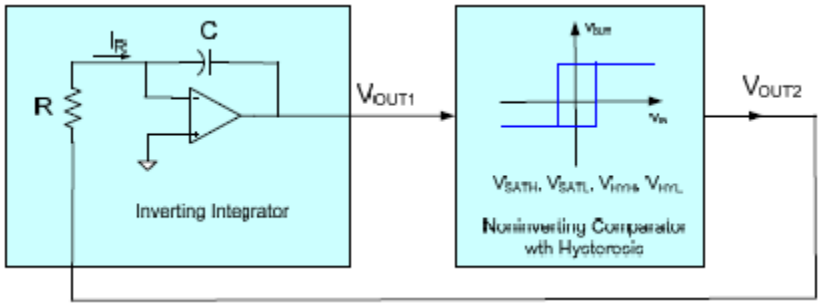


Figure 12.1

The two separate outputs in Figure 12.1 are shown in Figure 12.2. As you can see, the inverting integrator creates a triangle wave. This triangle wave, when compared to a separate signal fed into the non-inverting comparator creates a square wave.

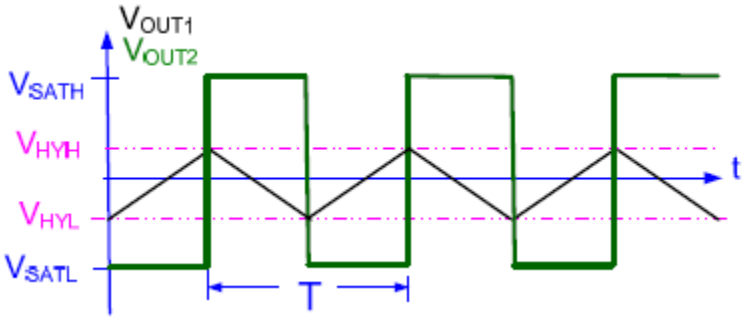


Figure 12.2

The triangle wave from the output of the inverting integrator is also known as a chopping or carrier signal. In order to control the duty cycle of our PWM waveform, we utilize an analog output from the NI-DAQ to vary the command signal sent into the comparator, as shown in Figure 12.3.

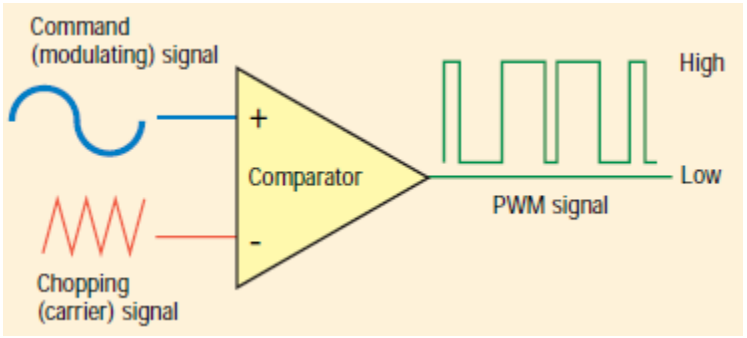


Figure 12.3

The comparator circuitry is shown in Figure 12.4. V_{IN} represents the input triangle waveform and V_{REF} represents the varying analog input from the NI-DAQ that we use to control the duty cycle.

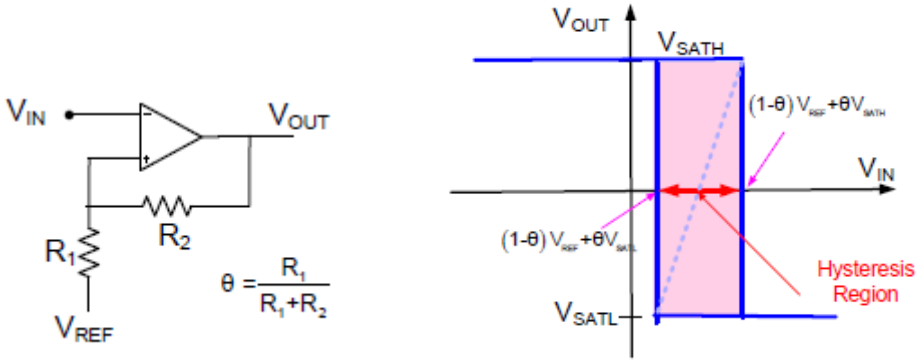


Figure 12.4

Refer to Appendix B-2 for the overall schematic of the PWM circuitry. As you can see, we use a modification of an inverting integrator. The main modification we made was adding a transistor whose base is controlled by the square wave output, the collector is connected in series to a resistor to the inverting input of the op amp controlling the triangle wave, and the emitter is connected to ground. This implementation ensures that the inverting integrator maintains an output between the control voltage and ground.

12.2: Calculations

$$f = \frac{1}{RC}\frac{V_{SATL}V_{SATH}}{(V_{HYH} - V_{HYL})(V_{SATL} - V_{SATH})}$$

$$V_{SATH} = V_{DD} \qquad V_{SATL} = V_{SS} = -V_{DD} \qquad \Theta = \frac{R_1}{R_1 + R_2}$$

$$V_{HYH} = \frac{\Theta}{1-\Theta}V_{DD} \qquad V_{HYL} = \frac{-\Theta}{1-\Theta}V_{DD}$$

$$f = \frac{1}{2RC}\frac{1-\Theta}{\Theta}$$

Section 13: Battery/Inverter

13.1: Batteries

When there is no wind present, a backup source is needed to power the load. For this task, the system uses two 12V batteries in series with each other. This amount of voltage used is due to the minimum of 21V needed to be delivered to the inverter. In order to prevent damage to the batteries, the voltage level shouldn't exceed 26 volts or go lower than 17 volts. A picture of the type of battery used along with the specifications is used in Figure 13.1.

Figure 13.1

13.2: Inverter

From the turbine or batteries, a DC signal is sent to the inverter. An inverter's task is to take a DC signal and send out the 60 Hz required AC signal to the load. The input voltage ranges from 21 to 34 volts for operation. For this reason, the user needs to make sure the battery is above 21V for use of backup power to the system. Figure 13.2 shows a picture of the inverter used and Figure 13.3 shows the specifications of the inverter used.

Figure 13.2

Specifications	Values
Nominal DC Input Voltage	24V
Output Current Rating	20.8A
DC Input Voltage Range	21-34V

Figure 13.3 - GTFX2524 Specifications

Section 14: AC Load

The goal of the project is to deliver wind power to a certain load. The load for this system is two light bulbs and an outlet. An outlet is used if the user wants to simulate even larger loads than the light bulbs. Our system is using standard 75 or 150 watt light bulbs and a switch that turns the second light bulb on or off. All three of these loads can give an observer many possibilities for experimentation. A picture of the load used can be seen below in Figure 14.1.

Figure 14.1

Section 15: Concluding Remarks

This wind turbine simulation project is intended to be educational for those that implemented the system and for any future users. If any of the discussed circuitry in the previous sections is damaged or incomplete upon use of the system, please feel free to bypass or rebuild. But any bypassing of circuitry must be done with prior knowledge of circuits and by studying this document. Notice that any Plexiglas cases with circuitry are not mounted to the table. The reasoning is for any potential user to implement their own circuitry to test their understanding of the system.

Disclaimer: Any circuitry not discussed in the previous sections can be found in the schematics in Appendix B. The system schematics are subject to change. The schematics in this document are for understand the full system and how it works. For completed schematics see computer co1301-sdmay12-24 in 1102 Coover. Furthermore, any devices or software that was not developed by team SDMay12-24 should have a user's manual (see References), where users should inquire for more detailed information.

Figure 2.2 shows the existing circuit that was implemented from last year's team. Figure 15.1 shows the system rebuilt in its optimized format that was discussed in the above sections. Notice the new motor mount, with the generator exposed from the turbine. The Plexiglas boxes show circuitry that was rebuilt from the turbine interior circuitry. Not show in Figure 15.1, are the batteries, inverter, computer, VFD, power analyzer, and +/- 15 V supply.

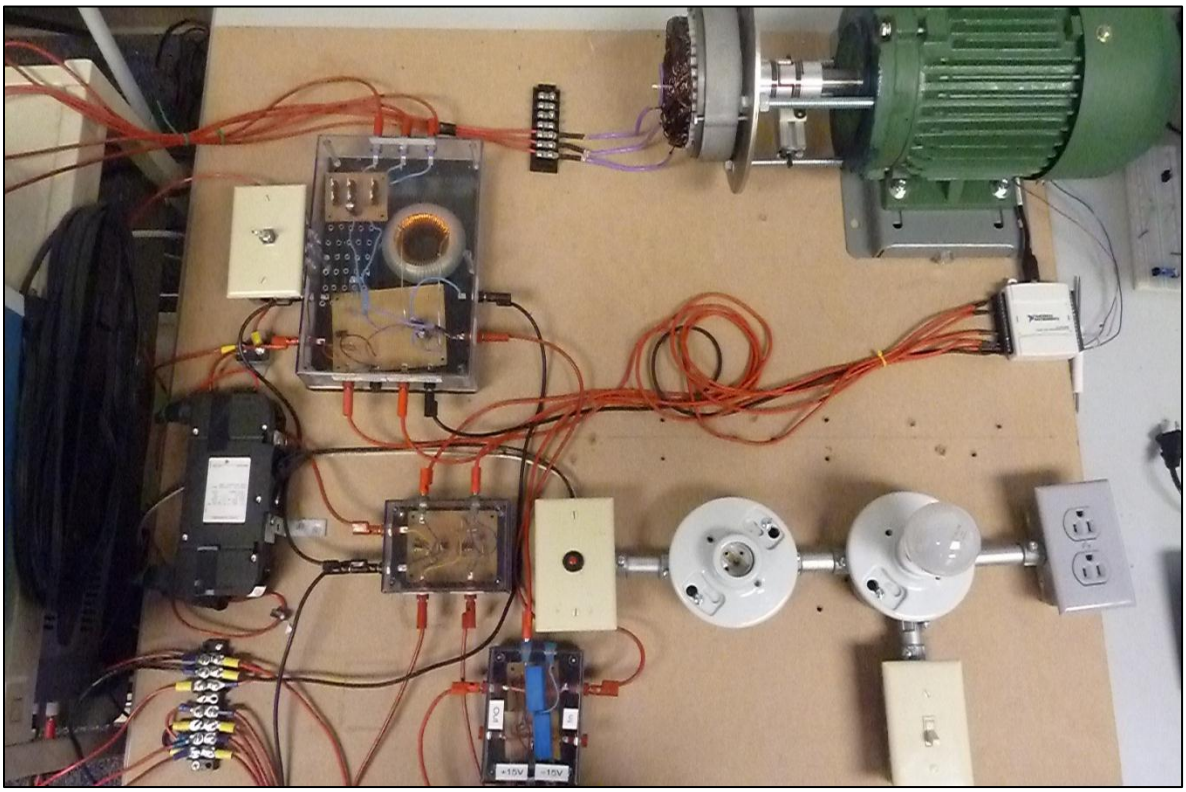


Figure 15.1 – Finalized System

References

Source 1: Bishop, Robert H. *LabVIEW 8 Student Edition.* Upper Saddle River, NJ: Person Education Inc., 2007. Print Manual.
This manual is intended for those working in LabVIEW with the basics to more complex systems. SDMAY12_24 group uses this manual to look up shortcuts, implementing virtual instruments, using MathScript, etc.

Source 2: OutBack Power Systems. *FX Series Inverter/Charger FX/VFX/GTFX/GVFX/MOBILE Installation Manual.* Arlington, WA: OutBack Power Systems, June 2008 REV B. Installation Manual
This manual explains the operating constraints of the inverter we use for this project. We are using the model GTFX2524.

Source 3: Southwest Windpower, Inc. *Air X Owner's Manual, Installation-Operation-Maintenance.* Flagstaff, Arizona: Southwest Windpower, Inc. October 2008. Owner's Manual
.
This owner's manual gives operating constraints of the wind turbine that SDMAY12-24 uses for their project. We use the LAND model with serial number 117566.

Source 4: Ryan Semler, Shonda Butler, Chad Hand, Luke Rupiper, Andrew Nigro, "sdmay11-01 Wind Turbine Design." SDMAY11-01. May 2011, http://seniord.ece.iastate.edu/may1101/index.html.

This was the projects preceding team (Phase III). We are continuing from where they finished. Using the devices that they put in place, we are to meet our project needs. Also, to show how the current system is operating we will have to use their schematics that they designed.

Source 5: Trzynadlowski, Andrzej M. *Introduction to Modern Power Electronics*. Hoboken, NJ: John Wiley & Sons, Inc., 2010. Text Book.

This text book is used for an undergraduate class for electrical engineers (EE 452) at ISU. The information on the Buck-boost can be primarily found in section 8.2.3.

Source 6: "Buck-Boost Converter." Wikipedia, Wikipedia Foundation, Inc. August 2011, http://en.wikipedia.org/wiki/Buck%E2%80%93boost_converter

Figure 11.1 was used from this Wikipedia site.

http://en.wikipedia.org/wiki/Mandatory_renewable_energy_target

http://www.prnewswire.com/news-releases/iowa-leads-nation-in-wind-energy-generation-122435353.html

http://www.allaboutcircuits.com/vol_3/chpt_3/4.html figure 10.1

http://en.wikipedia.org/wiki/Rectifier#Applications

Appendix A: Operational Manual

WARNING: This lab contains moving parts and high currents. The user should always be accompanied with a lab partner when operating any equipment with this project. The user and lab partner should inspect all wiring before operation. The lab partner should double check any work pertaining to the user and any equipment operation. Both individuals should have prior knowledge of circuits before handling any equipment. Use this operation manual as a check-off list when starting up the lab. System schematics can be found in Appendix B.

I. Check Wiring

A. Verify the wiring is correct by checking / studying the schematics of the system.

B. Ensure all banana plugs are in the correct slots, and that plugs are fitting tightly.

~~II. Turn ON "safety battery switch" (Appendix B-3)~~

~~A. When the switch is ON the batteries are connected to the system and therefore could drain any stored energy into devices in the circuitry.~~

~~B. Please turn OFF the batteries when done using the lab.~~

~~C. Inside the "switch box" there is a logic switch, which is controlled through LabVIEW. This switch is hardwired into the system.~~

~~D. Note: The system can run without the batteries, but it is not ideal to run the full system simulation (i.e. file ____).~~

III. Turn ON "Inverter Switch" (Appendix B-3)

A. Now the system is connected to the inverter for DC/AC inversion.

B. Please turn the "Inverter Switch" OFF when done running the system.

C. Trouble shooting

1. If Status Inverter light is OFF and Battery Full light is ON, check Inverter On/Off Jumper.

IV. Turn ON +/- 15 VDC Rail (E3631A)

A. The +/- 15 VDC source is used to power the op-amps and the CTs.

B. WARNING: Turning these on out of sequence could cause device damage.

C. Please turn the +/- 15 VDC rail OFF when done running the system.

V. Turn ON the 3-phase power supply (Kikusui PCR6000LA)

A. Read the Kikusui PCR6000LA manual on full operation.

B. Turn the Kikusui PCR6000LA OFF when done running the system.

VI. Turn ON the power analyzer

A. Read the manual on full operation.

B. Turn the power analyzer OFF when done running the system.

C. When USB connection is plugged into power analyzer, then the power analyzer must be ON for LabVIEW to connect to Kikusui PCR6000LA 3-phase power supply.

VII. Turn ON the WESTPOINTE 4" fan

A. This fan is for cooling the IGBT heat sink in the buck-boost.

VIII. Log into the project account with the correct log-in password.

A. For running an automated system (using real wind data), open file Wind Simulation FINAL Phase IV.vi found on the desktop.

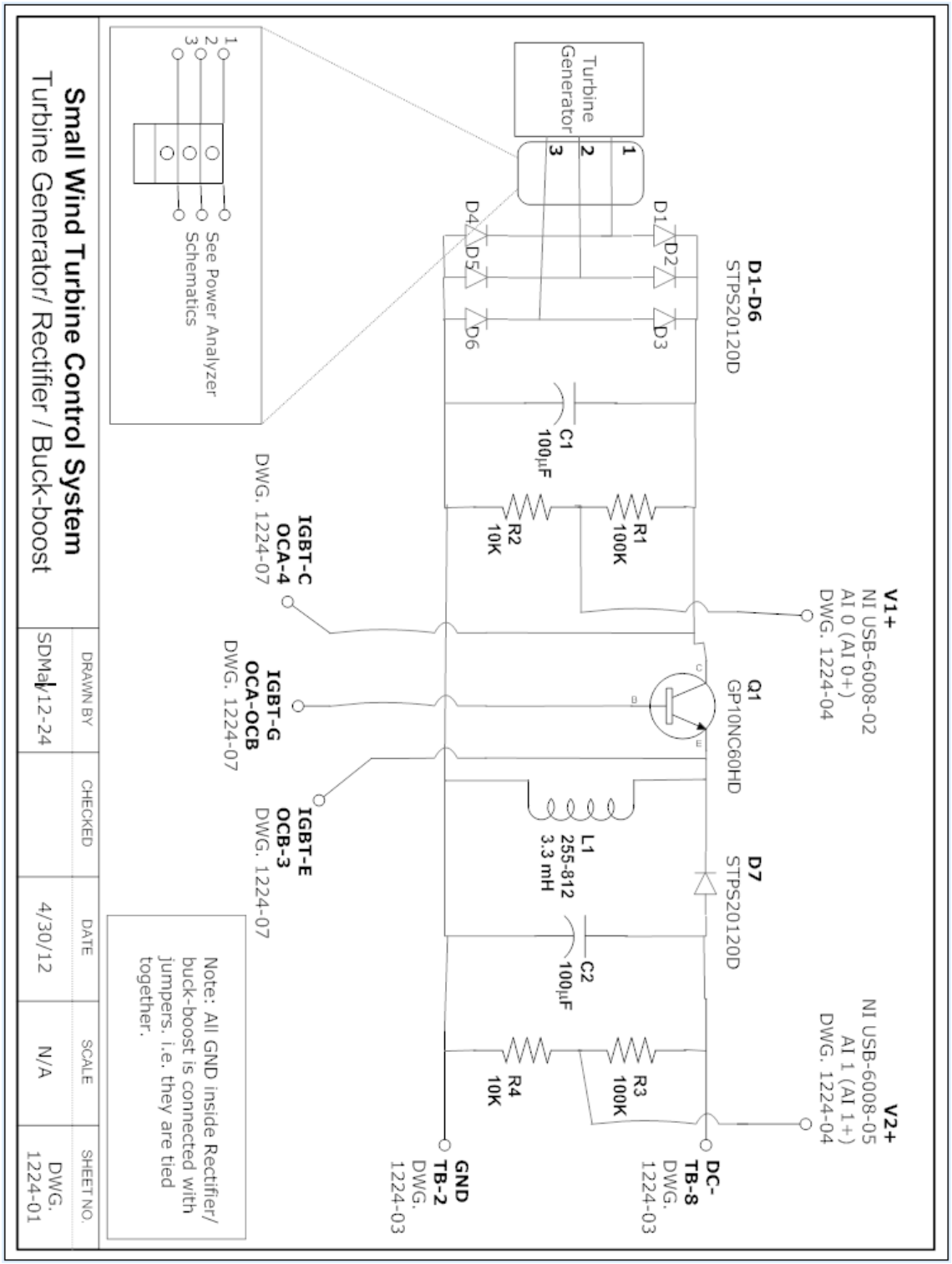
1. Hit the "RUN" button at the top left corner.

B. For running the system manually, open file RPM Control2.vi found on the desktop.

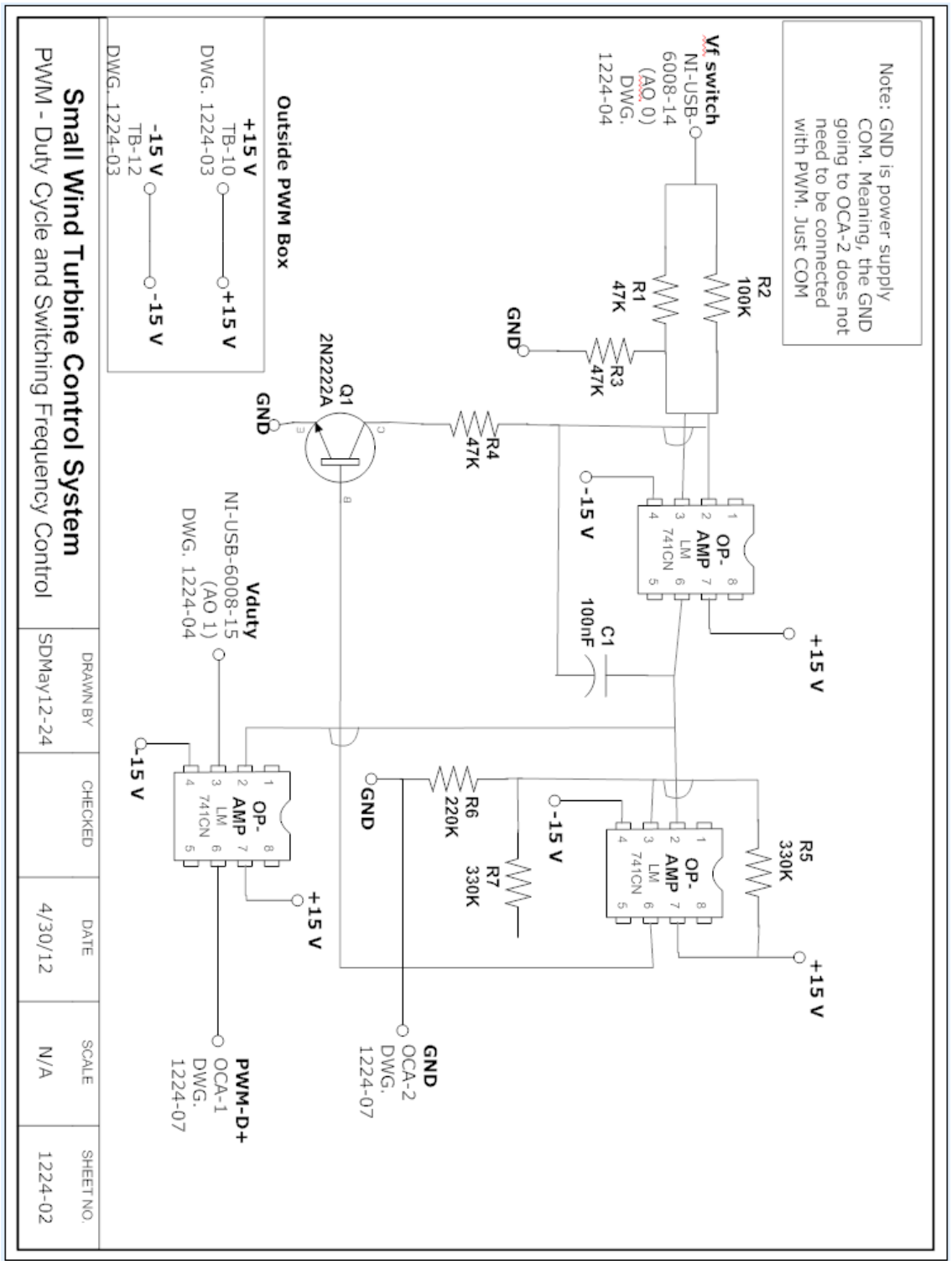
1. WARNING: This "manual" LabVIEW file is for those that are familiar with motor control. The user is advised to read through section 7 on motor control in the final document of SDMay12-24. Also, the user should do any additional research required on induction motors. Failure to do so will result in overheating of the motor and/or damage to the internal windings.

2. Here, the user simply inputs slip and RPM of the machine. After hitting the "RUN" button, the system will maintain the stated slip and RPM.

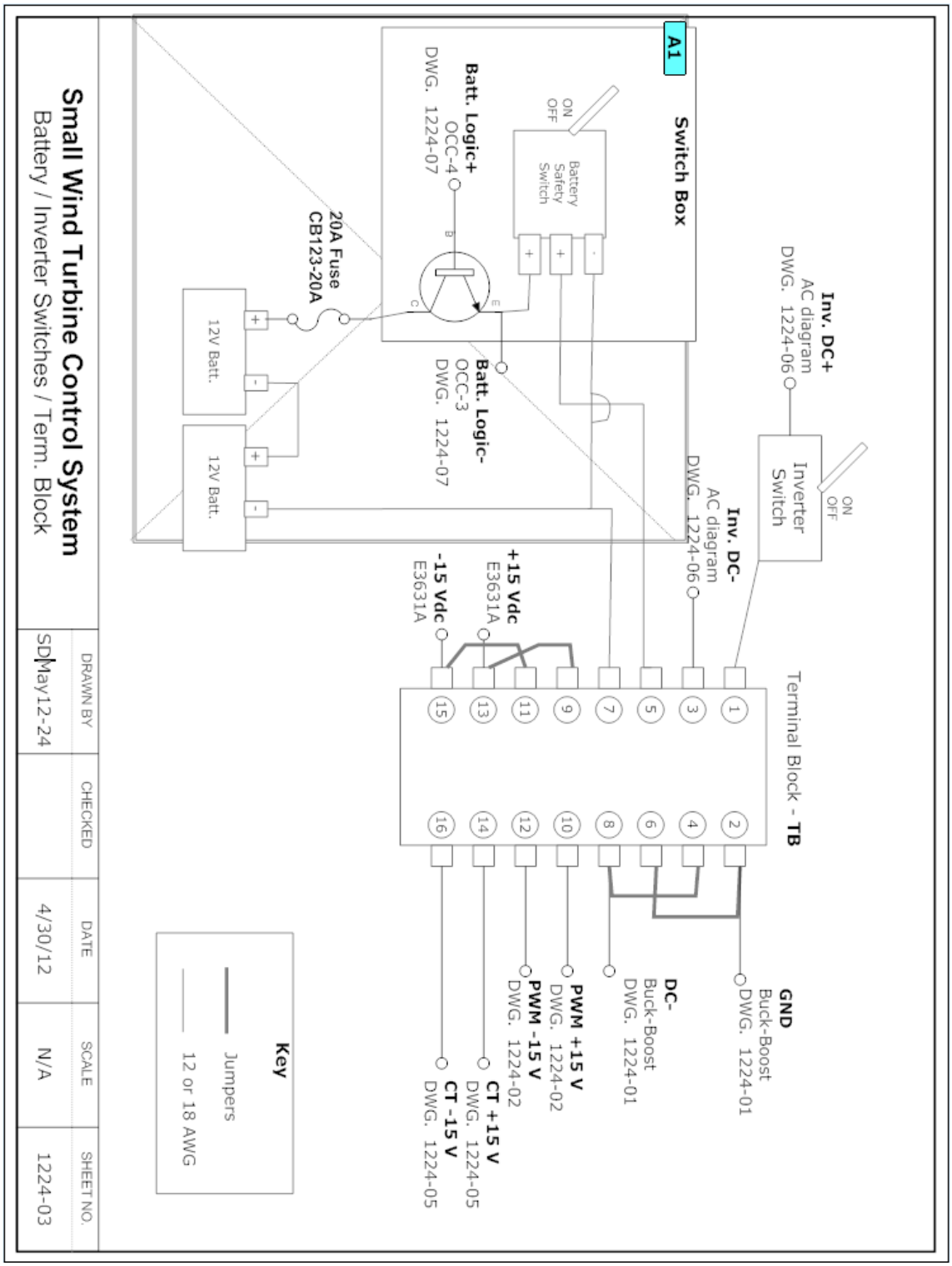
Appendix B-1


Small Wind Turbine Control System
Turbine Generator/ Rectifier / Buck-boost
DRAWN BY
SDMay12-24
CHECKED
DATE
4/30/12
SCALE
N/A
SHEET NO.
DWG. 1224-01
Turbine Generator
1
2
3
See Power Analyzer Schematics
D1-D6
STPS20120D
D1
D2
D3
D4
D5
D6
C1
100µF
R1
100K
R2
10K
V1+
NI USB-6008-02
AI 0 (AI 0+)
DWG. 1224-04
Q1
GP10NC60HD
IGBT-C
OCA-4
DWG. 1224-07
IGBT-G
OCA-OCB
DWG. 1224-07
IGBT-E
OCB-3
DWG. 1224-07
L1
255-812
3.3 mH
D7
STPS20120D
C2
100µF
R3
100K
R4
10K
V2+
NI USB-6008-05
AI 1 (AI 1+)
DWG. 1224-04
DC-
TB-8
DWG. 1224-03
GND
TB-2
DWG. 1224-03
Note: All GND inside Rectifier/ buck-boost is connected with jumpers. i.e. they are tied together.

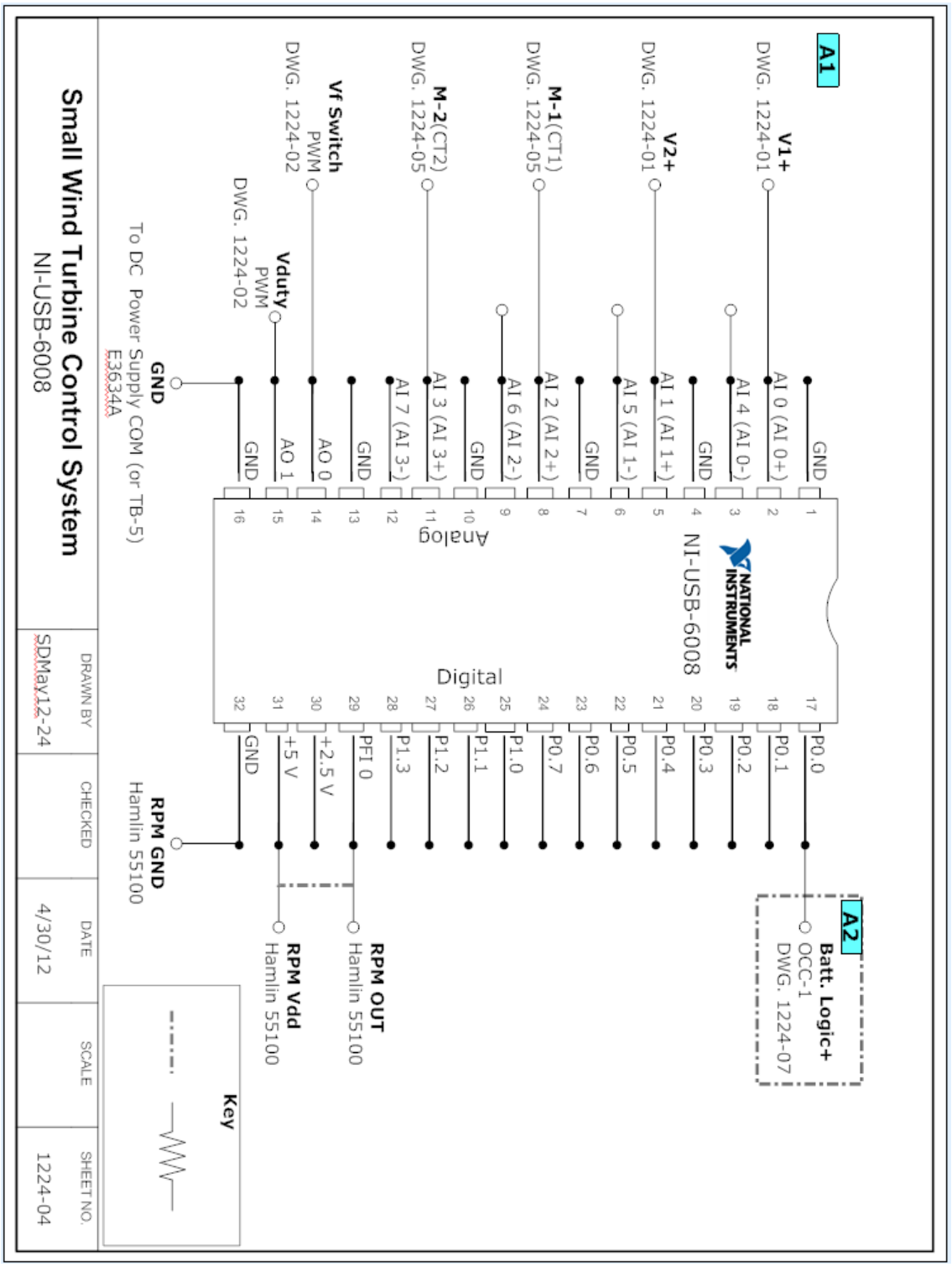
Appendix B-2


Note: GND is power supply COM. Meaning, the GND going to OCA-2 does not need to be connected with PWM. Just COM
Vf switch
NI-USB-6008-14 (AO 0) DWG. 1224-04
R2 100K
R1 47K
R3 47K
GND
Q1 2N2222A
R4 47K
-15 V
C1 100nF
OP-AMP LM 741CN
+15 V
R5 330K
R6 220K
R7 330K
Outside PWM Box
+15 V TB-10 DWG. 1224-03
-15 V TB-12 DWG. 1224-03
Vduty
NI-USB-6008-15 (AO 1) DWG. 1224-04
GND OCA-2 DWG. 1224-07
PWM-D+ OCA-1 DWG. 1224-07
Small Wind Turbine Control System
PWM - Duty Cycle and Switching Frequency Control
DRAWN BY SDMay12-24
CHECKED
DATE 4/30/12
SCALE N/A
SHEET NO. 1224-02

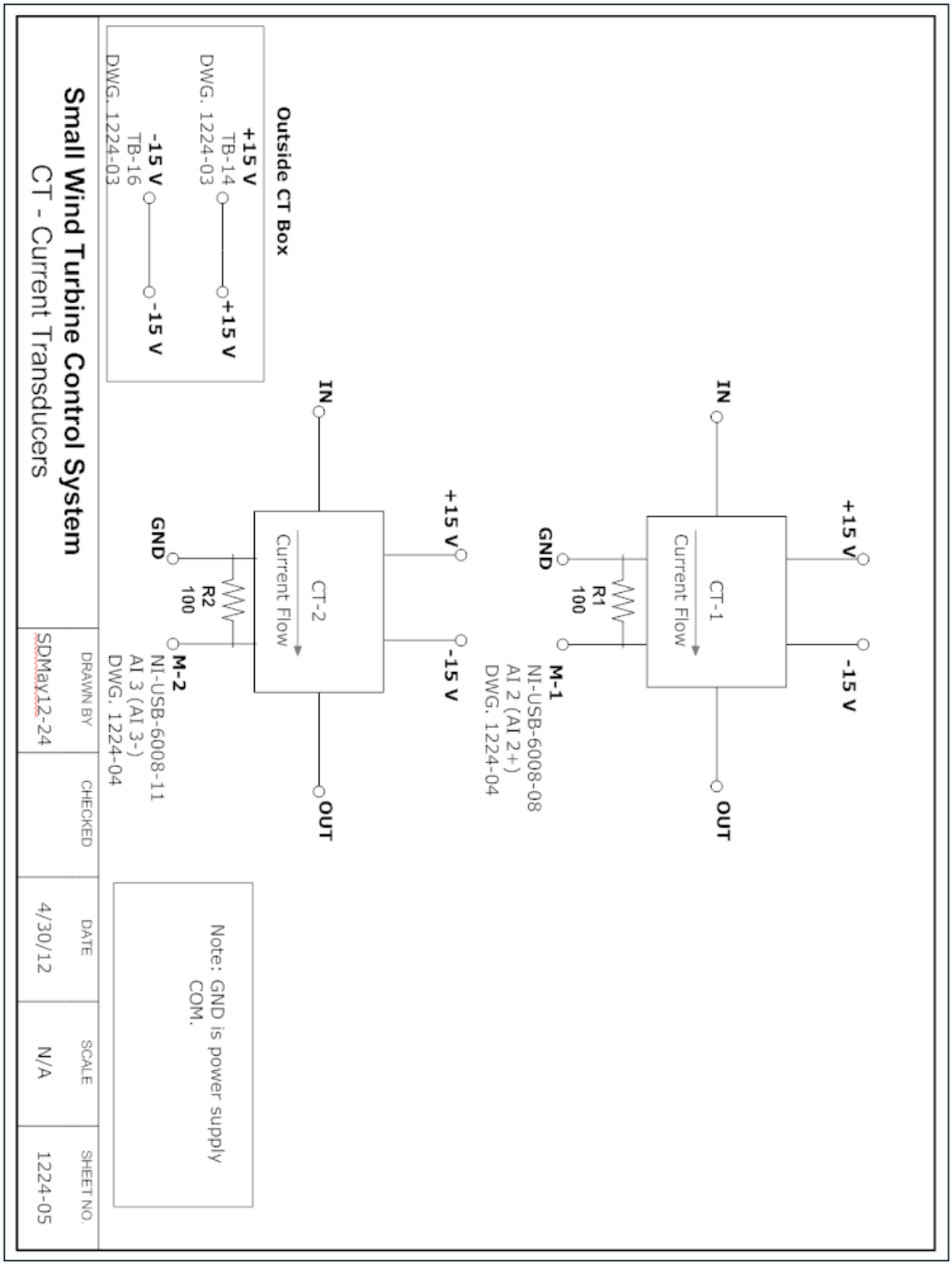
Appendix B-3


Small Wind Turbine Control System
Battery / Inverter Switches / Term. Block
DRAWN BY
SDMay12-24
CHECKED
DATE
4/30/12
SCALE
N/A
SHEET NO.
1224-03
A1
Switch Box
Inv. DC+
AC diagram
DWG. 1224-06
Inverter Switch
ON
OFF
Inv. DC-
AC diagram
DWG. 1224-06
Terminal Block - TB
GND
Buck-Boost
DWG. 1224-01
DC-
Buck-Boost
DWG. 1224-01
PWM +15 V
DWG. 1224-02
PWM -15 V
DWG. 1224-02
CT +15 V
DWG. 1224-05
CT -15 V
DWG. 1224-05
+15 Vdc
E3631A
-15 Vdc
E3631A
Batt. Logic+
OCC-4
DWG. 1224-07
Batt. Logic-
OCC-3
DWG. 1224-07
Battery Safety Switch
ON
OFF
20A Fuse
CB123-20A
12V Batt.
12V Batt.
Key
Jumpers
12 or 18 AWG

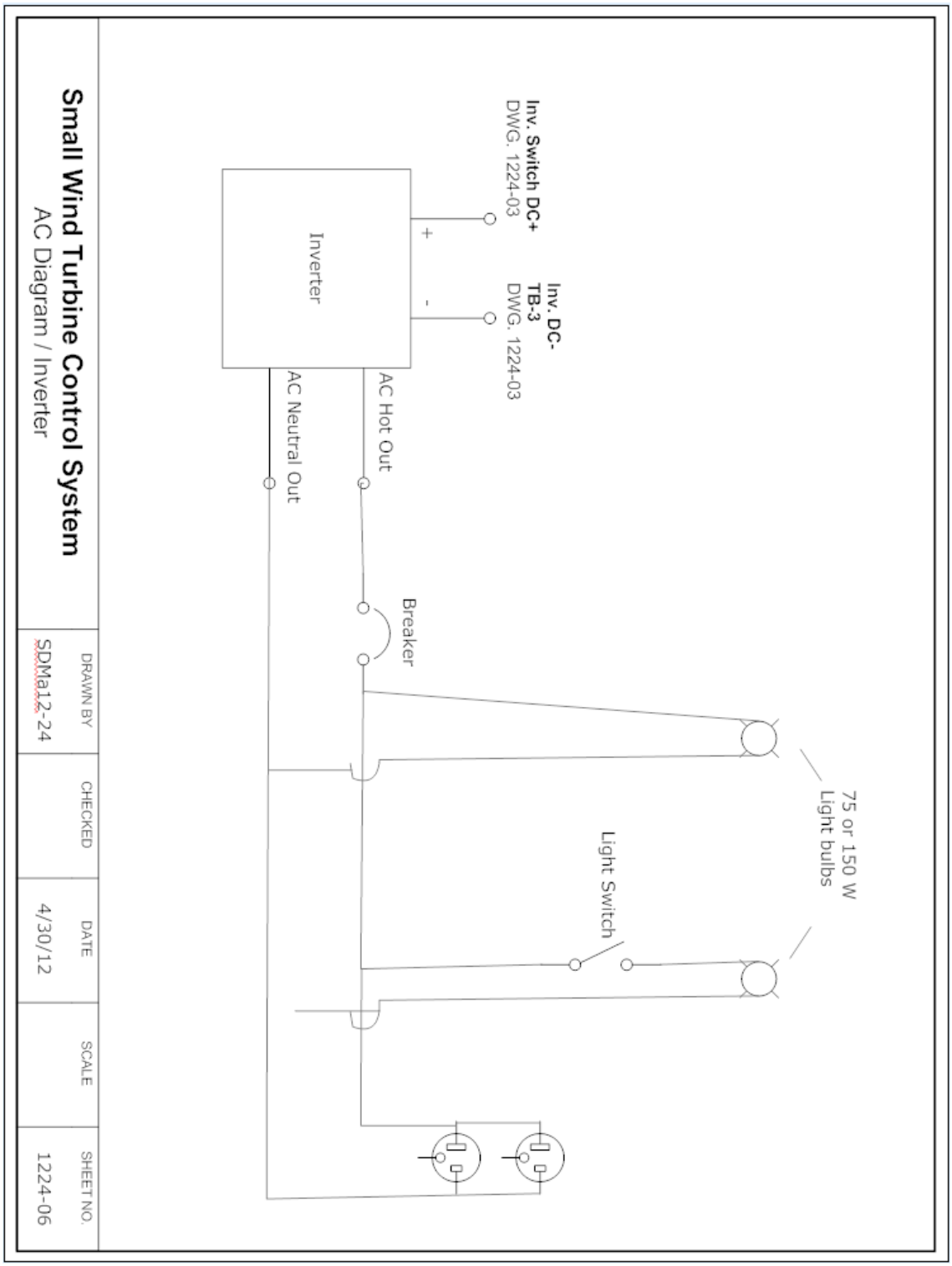
Appendix B-4


A1
V1+
DWG. 1224-01
V2+
DWG. 1224-01
M-1(CT1)
DWG. 1224-05
M-2(CT2)
DWG. 1224-05
Vf Switch
PWM
DWG. 1224-02
Vduty
PWM
DWG. 1224-02
GND
To DC Power Supply COM (or TB-5)
E36344A
GND
AI 0 (AI 0+)
AI 4 (AI 0-)
GND
AI 1 (AI 1+)
AI 5 (AI 1-)
GND
AI 2 (AI 2+)
AI 6 (AI 2-)
GND
AI 3 (AI 3+)
AI 7 (AI 3-)
GND
AO 0
AO 1
GND
Analog
NI-USB-6008
Digital
P0.0
P0.1
P0.2
P0.3
P0.4
P0.5
P0.6
P0.7
P1.0
P1.1
P1.2
P1.3
PFI 0
+2.5 V
+5 V
GND
RPM GND
Hamlin 55100
A2
Batt. Logic+
OCC-1
DWG. 1224-07
RPM OUT
Hamlin 55100
RPM Vdd
Hamlin 55100
Key
Small Wind Turbine Control System
NI-USB-6008
DRAWN BY
SDMay12-24
CHECKED
DATE
4/30/12
SCALE
SHEET NO.
1224-04

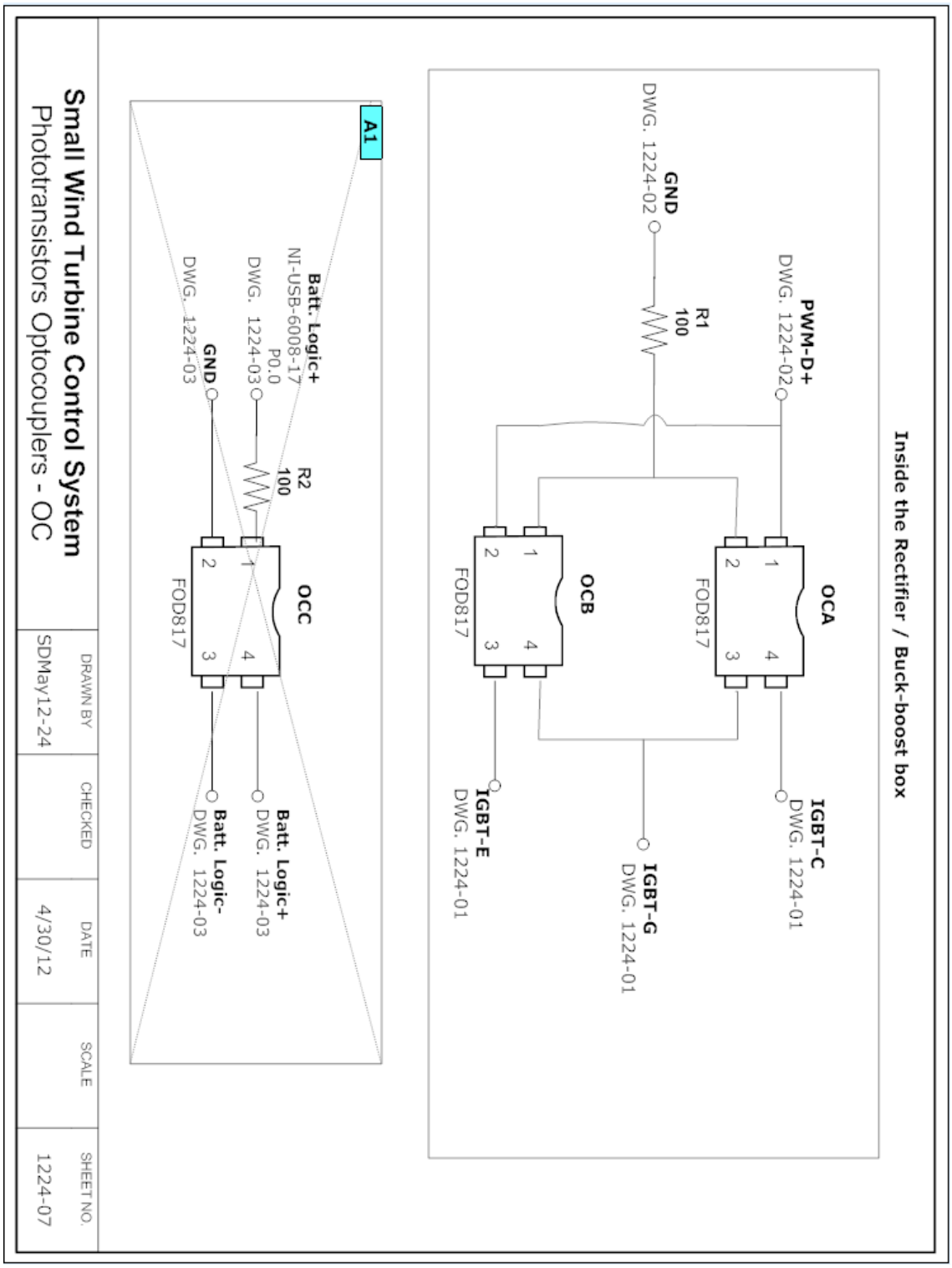
Appendix B-5


Small Wind Turbine Control System
CT - Current Transducers
DRAWN BY
SDMay12-24
CHECKED
DATE
4/30/12
SCALE
N/A
SHEET NO.
1224-05
Outside CT Box
+15 V
TB-14
DWG. 1224-03
-15 V
TB-16
DWG. 1224-03
+15 V
-15 V
IN
CT-1
Current Flow
OUT
+15 V
-15 V
GND
R1
100
M-1
NI-USB-6008-08
AI 2 (AI 2+)
DWG. 1224-04
IN
CT-2
Current Flow
OUT
+15 V
-15 V
GND
R2
100
M-2
NI-USB-6008-11
AI 3 (AI 3-)
DWG. 1224-04
Note: GND is power supply COM.

Appendix B-6


Small Wind Turbine Control System
AC Diagram / Inverter
DRAWN BY
SDMa12-24
CHECKED
DATE
4/30/12
SCALE
SHEET NO.
1224-06
Inv. Switch DC+
DWG. 1224-03
Inv. DC-
TB-3
DWG. 1224-03
+
-
Inverter
AC Hot Out
AC Neutral Out
Breaker
75 or 150 W
Light bulbs
Light Switch

Appendix B-7


Inside the Rectifier / Buck-boost box
PWM-D+
DWG. 1224-02
GND
DWG. 1224-02
R1
100
OCA
FOD817
IGBT-C
DWG. 1224-01
OCB
FOD817
IGBT-G
DWG. 1224-01
IGBT-E
DWG. 1224-01
A1
Batt. Logic+
NI-USB-6008-17
P0.0
DWG. 1224-03
GND
DWG. 1224-03
R2
100
OCC
FOD817
Batt. Logic+
DWG. 1224-03
Batt. Logic-
DWG. 1224-03
Small Wind Turbine Control System
Phototransistors Optocouplers - OC
DRAWN BY
SDMay12-24
CHECKED
DATE
4/30/12
SCALE
SHEET NO.
1224-07